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Color sextet vector bosons and same-sign top quark pairs at the LHC

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ABSTRACT

We investigate the production of beyond-the-standard-model color sextet vector bosons at the Large Hadron Collider and their decay into a pair of same-sign top quarks. We demonstrate that the energy of the charged lepton from the top quark semi-leptonic decay serves as a good measure of the top quark polarization, which, in turn determines the quantum numbers of the boson and distinguishes vector bosons from scalars.

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1. Introduction

The cross section for production of top quarks is relatively high at the energies of the Large Hadron Collider (LHC). While conventional mechanisms produce either a single top quark or a top–antitop pair, it is important to be alert to the observation of a pair of same-sign top quarks. One consequence would be the appearance of a pair of same-sign leptons with large transverse momentum. In a recent Letter, we explore the potential for discovery of an exotic color sextet scalar in the production of a pair of same-sign top quarks in early runs of the LHC at 7 TeV [1]. The standard model (SM) backgrounds are small. We demonstrate that one can measure the scalar mass and the top quark polarization, and confirm the scalar nature of the resonance with 1 fb^{-1} of integrated luminosity. Moreover, the top quark polarization distinguishes gauge triplet- and singlet-scalars. In the present manuscript, we address color sextet *vector* production in same-sign top quark pair-production, and we show that its discovery, and the determination of its properties, could also be accomplished with early LHC data.

Important in our analysis is the recognition that among the products of semi-leptonic top quark decay, the direction of the charged-lepton is highly correlated with the top quark spin. The top quark polarization can be measured from the distribution in $\cos\theta$ [2], the cosine of helicity angle between the charged-lepton momentum in the top quark rest frame and the top quark momentum in the center-of-mass frame of the production process (i.e. the rest frame of the parent scalar or vector). The $SU(2)_L$ gauge triplet scalars decay to $t_L t_L$, and the $SU(2)_L$ gauge singlet scalars to $t_R t_R$. Here, t_L and t_R denotes top quarks with left-handed and right-handed polarization. In either case, both top quarks produce the same angular distribution, either $(1 - \cos\theta)/2$ ($t_L t_L$) or $(1 + \cos\theta)/2$ ($t_R t_R$), allowing unambiguous identification of the scalar [1]. An $SU(3)_C$ color sextet vector decays into a $t_L t_R$ pair. In this case, the observed inclusive angular distribution in the final state would be a flat, a sum of the shapes from the t_L and the t_R decays. The flat profile would distinguish a vector from a scalar, but it also would admit a mechanism that yields unpolarized top quarks.

In this Letter we establish that one can separate the angular distributions corresponding to t_L and t_R from the color sextet vector decay into a $t_L t_R$ pair. The solution relies of the introduction of asymmetric cuts on the momenta of the leptons from the top quark decays.

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2. The Model

The most general $SU(3)_C \times SU(2)_L \times U(1)_Y$ effective invariant Lagrangian for color sextet scalars Φ and vectors V_μ has the form [3–10]

$$\begin{aligned} \mathcal{L} = & (g_{1L} \bar{q}_L^c i \tau_2 q_L + g_{1R} \bar{u}_R^c d_R) \Phi_{6,1,1/3} \\ & + g'_{1R} \bar{d}_R d_R \Phi_{6,1,-2/3} + g'_{1R} \bar{u}_R u_R \Phi_{6,1,4/3} \\ & + g_{3L} \bar{q}_L^c i \tau_2 \tau q_L \Phi_{6,3,1/3} \\ & + g_2 \bar{q}_L^c \gamma_\mu d_R V_{6,2,-1/6}^\mu + g'_2 \bar{q}_L^c \gamma_\mu u_R V_{6,2,5/6}^\mu + \text{h.c.}, \end{aligned} \quad (1)$$

where $q_L = (u_L, d_L)$ denotes the left-handed quark doublet, u_R and d_R are the corresponding right-handed gauge singlet fields, and $q^c \equiv \bar{q}^T$ is the charge conjugated quark field. For the sake of simplicity, color and generation indices are omitted. The subscripts on the Φ and V fields denote the standard model gauge quantum numbers ($SU(3)_C, SU(2)_L, U(1)_Y$).¹

We are interested in same-sign top quark pair production via a sextet vector decay. Only the axial-vector part of the coupling contributes. The vanishing of the pure vector coupling can be understood as follows. Since the interaction involves two identical q quarks, there are two ways to use the fields in the Lagrangian to destroy the quark. The current is

$$\begin{aligned} J^\mu = & K_{ab}^M \bar{q}_a^c \gamma^\mu (g_v + g_a \gamma_5) q_b - K_{ba}^M \bar{q}_b^c \gamma^\mu (g_v + g_a \gamma_5) q_a \\ = & K_{ab}^M \{ \bar{q}_a^c \gamma^\mu (g_v + g_a \gamma_5) q_b - \bar{q}_b^c \gamma^\mu (g_v + g_a \gamma_5) q_a \}. \end{aligned} \quad (2)$$

The K_{ab}^M are Clebsch–Gordan coefficients; a and b are the color indices in the fundamental representation; M is the color index in the sextet representation; and g_v (g_a) denotes the vector (pseudo-vector) coupling. The minus sign between the two terms arises from Fermi–Dirac statistics, and the symmetric feature of the sextet representation is used in the last step. Using simple algebra, one can show that

$$\bar{q}_b^c \gamma^\mu (g_v + g_a \gamma_5) q_a = \bar{q}_a^c \gamma^\mu (g_v - g_a \gamma_5) q_b. \quad (3)$$

Therefore, only the pseudo-vector interactions remain while the vector interactions vanish.

The effective coupling of the color sextet vector to a pair of identical quarks (qq) is

$$\mathcal{L}_{\text{int}} = \frac{g_{qq}}{2} K_{ab}^M \bar{q}_a \gamma_\mu \gamma_5 q_b^c V_M^\mu + \text{h.c.}, \quad (4)$$

where g_{qq} is the coupling strength. Without loss of generality, we concentrate on real and flavor-conserving couplings in this work.

The coupling of the vector to two up-type quarks is largely constrained by the measurement of $D^0 - \bar{D}^0$ mixing which is affected by the vector at the tree level. The $|\Delta C = 2|$ Hamiltonian induced by V is

$$\mathcal{H}_{\Delta C=2} = \frac{2g_{uu}g_{cc}}{m_V^2} (C_3(\mu) Q_3 + C_2(\mu) Q_2). \quad (5)$$

The four-fermion operators Q_2 and Q_3 are

$$Q_2 = (\bar{u}_{La} \gamma^\mu c_{La})(\bar{u}_{Rb} \gamma_\mu c_{Rb}), \quad (6)$$

$$Q_3 = (\bar{u}_{La} c_{Ra})(\bar{u}_{Rb} c_{Lb}), \quad (7)$$

and the Wilson coefficients are

$$C_2(m_V) = -1, \quad C_3(m_V) = 2.$$

The vector's contribution to $\Delta m_D \equiv |m_{D^0} - m_{\bar{D}^0}|$ is

$$\begin{aligned} \Delta m_D = & \left| \Re \left(\frac{2 \langle \bar{D}^0 | \mathcal{H} | D^0 \rangle}{2m_D} \right) \right| \\ = & \frac{1}{m_D} \frac{2g_{uu}g_{cc}}{m_V^2} |C_2 \langle Q_2 \rangle + C_3 \langle Q_3 \rangle|, \end{aligned} \quad (8)$$

where the hadron matrix elements are [12]

$$\begin{aligned} \langle Q_2 \rangle = & -\frac{5}{6} f_D^2 m_D^2 B_D, \\ \langle Q_3 \rangle = & \frac{7}{12} f_D^2 m_D^2 B_D, \end{aligned} \quad (9)$$

with $f_D = 222.6 \pm 16.7_{-2.4}^{+2.3}$ MeV, $m_D = 1865$ MeV, and $B_D = 0.82$ [13]. To be consistent with the measured Δm_D [14],

$$x_D = \frac{\Delta m_D}{\Gamma_D} \sim 8 \times 10^{-3},$$

$$\Gamma_D = 1.6 \times 10^{-12} \text{ GeV},$$

the coupling g_{qq} is stringently constrained:

$$g_{uu}g_{cc} \lesssim 1.6 \times 10^{-8} \quad (10)$$

for $m_V \simeq 1$ TeV, after an enhancement factor ~ 2.1 is included from the QCD running of the Wilson coefficients from the scale m_V to m_c .

This strong constraint on the product $g_{uu}g_{cc}$ allows freedom for the production of V at the LHC if the coupling g_{cc} to the second generation quarks is minimized. Alternatively, the first generation may be suppressed while the second generation is not, but such sea-quark initiated processes are relatively suppressed.

For the choice $g_{uu} = 1$, we show the cross section for V production via the process $uu \rightarrow V$ at the LHC in Fig. 1(a), and the tt cross section via the process $uu \rightarrow tt$ in Fig. 1(b) for $g_{uu} = g_{tt} = 1$. The large cross sections arise from the large parton distribution functions for valence u quarks in the initial state. If the LHC energy is raised from 7 TeV to 14 TeV the cross section is increased by roughly a factor of 3 to 4. The $t\bar{t}$ production rate is much smaller owing to the suppression of the $\bar{u}u$ parton luminosity in a proton-proton collision. We focus our attention on the collider phenomenology of the tt pair production in early LHC experiments.

3. Discovery potential

The sample of events of interest to us is defined by two positively charged muons, two tagged b jets, and missing energy, with the muons and jets satisfying the kinematic cuts specified below. We veto events with extra particles in the region defined by the cuts.

We focus on the same-sign dilepton decay mode in which the W bosons from both $t \rightarrow Wb$ decays lead to a final state containing an electron or muon (denoted ℓ), $W \rightarrow \ell \nu$, accounting for about 5% of all tt decays. We concentrate on the clean $\mu^+ \mu^+$ final state because muon reconstruction has a large average efficiency of 95–99% within the pseudorapidity range $|\eta| < 2.4$ and transverse momentum range $5 \text{ GeV} \leq p_T \leq 1 \text{ TeV}$, while the charge mis-assigned fraction for muons with $p_T = 100 \text{ GeV}$ is less than 0.1% [16].

These events are characterized by two high-energy same-sign leptons, two jets (denoted j) from the hadronization of the b -quarks, and large missing energy (\cancel{E}_T) from two unobserved neutrinos. We generate the dominant backgrounds with ALPGEN [17]:

¹ The vector $V_{6,2,-1/6}$ is not considered here as it cannot decay into a top quark pair. Its collider phenomenology will be presented elsewhere [11].

Table 1

Signal and background cross sections (pb) before and after cuts, with $g_{uu} = g_{tt} = 1$, for six values of m_V (GeV) at the 7 TeV LHC. The decay branching ratios of the signal $\text{Br}(t\bar{t})$ are given in the second column. The “no cut” rates correspond to all lepton and quark decay modes of W bosons, whereas those “with cut” are obtained after all cuts, the restriction to $2\mu^+\nu$ ’s and with tagging efficiencies included.

m_V	$\text{Br}(t\bar{t})$	No cut	With cut	m_V	$\text{Br}(t\bar{t})$	No cut	With cut	Background	No cut	With cut
500	0.446	888.57	1.71	800	0.483	341.82	1.21	$t\bar{t}$	97.62	0.0004
600	0.466	665.82	1.76	900	0.487	244.62	0.92	$WWjj$	9.38	0.0006
700	0.477	477.09	1.53	1000	0.489	179.82	0.70	WWW/Z	0.03	0.00001

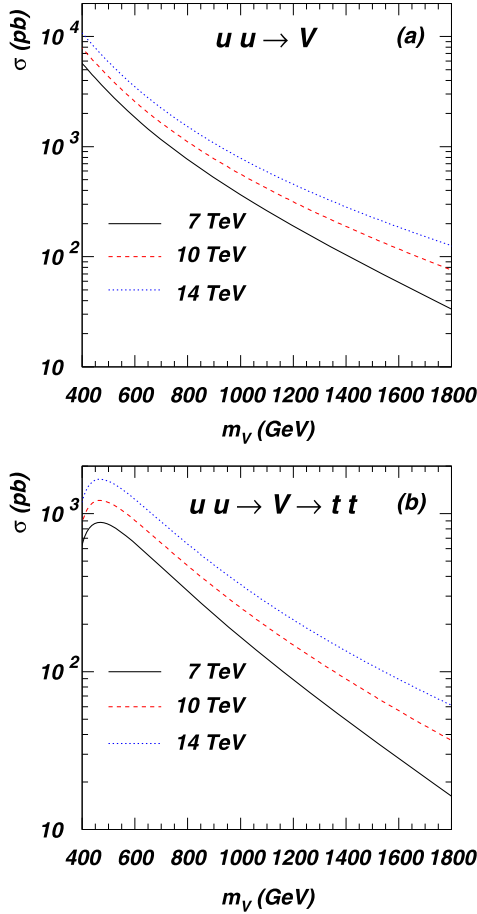


Fig. 1. Leading order cross sections (pb) for (a) V production via $uu \rightarrow V$ and (b) like-sign t -pair production via $uu \rightarrow V \rightarrow t\bar{t}$ at LHC energies: 7 TeV (solid), 10 TeV (dashed (red in the web version)), and 14 TeV (dotted (blue in the web version)) for $g_{uu} = g_{tt} = 1$. We use the CTEQ6L parton distribution functions [15] and choose the renormalization and factorization scales as m_V .

$$pp \rightarrow W^+(\rightarrow \ell^+\nu)W^+(\rightarrow \ell^+\nu)jj, \quad (11)$$

$$pp \rightarrow t\bar{t} \rightarrow bW^+(\rightarrow \ell^+\nu)\bar{b}(\rightarrow \ell^+)W^-(\rightarrow jj). \quad (12)$$

The first process ($WWjj$) is the SM irreducible background while the second ($t\bar{t}$) is a reducible background as it contributes when some tagged particles escape detection, carrying small p_T or falling out of the detector rapidity coverage. For example, one of the b -quarks decays into an isolated charged lepton while one of the two jets from the W^- boson decay is mis-tagged as a b -jet. Other SM backgrounds, e.g. triple gauge boson production (WWW , ZWW , and $WZg(\rightarrow b\bar{b})$), occur at a negligible rate after kinematic cuts, and are not shown here.

Since muon charge identification is not perfect, we remark that $t\bar{t}$ pair production could also be a background when μ^- leptons from the antitop quark decay are misidentified as μ^+ leptons. However, we find that this background is negligible. Its rate before any cuts is about

$$\begin{aligned} \sigma(t\bar{t}) \times \text{Br}(W^+ \rightarrow \mu^+\nu) \times \text{Br}(W^- \rightarrow \mu^-\bar{\nu}) \times \epsilon_{\mu^-\rightarrow\mu^+} \\ = (97.62 \times 10^3 \text{ fb}) \times \left(\frac{1}{9} \times \frac{1}{9}\right) \times 10^{-4} \simeq 0.12 \text{ fb}. \end{aligned} \quad (13)$$

After cuts, this background is reduced substantially below the level of the backgrounds listed in Table 1.

At the analysis level, all signal and background events are required to pass the following acceptance cuts:

$$\begin{aligned} n_j = 2, \quad n_{\mu^+} = 2, \quad p_T^j \geq 50 \text{ GeV}, \quad |\eta_j| \leq 2.5, \\ p_T^{\ell_{\text{greater}}} \geq 50 \text{ GeV}, \quad p_T^{\ell_{\text{lesser}}} \geq 20 \text{ GeV}, \quad |\eta_\ell| \leq 2.0, \\ \Delta R_{jj,\ell\ell} > 0.4, \end{aligned} \quad (14)$$

where we order the two charged leptons in the final state by their energies and label the more energetic lepton as “greater” and the other one as “lesser”. Owing to spin correlations, the charged lepton from right-handed top quark decay is more energetic than the one from the left-handed top quark decay. This difference motivates our asymmetric cut on the p_T of the two charged leptons. The separation ΔR in the azimuthal angle (ϕ)-pseudorapidity (η) plane between the objects k and l is

$$\Delta R_{kl} \equiv \sqrt{(\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2}. \quad (15)$$

We model detector resolution effects by smearing the final state energy according to

$$\frac{\delta E}{E} = \frac{\mathcal{A}}{\sqrt{E/\text{GeV}}} \oplus \mathcal{B}, \quad (16)$$

where we take $\mathcal{A} = 10(50)\%$ and $\mathcal{B} = 0.7(3)\%$ for leptons (jets). To account for b -jet tagging efficiencies, we demand two b -tagged jets, each with a tagging efficiency of 60%. We also apply a mistagging rate for charm-quarks $\epsilon_{c \rightarrow b} = 10\%$ for $p_T(c) > 50$ GeV. The mistag rate for a light jet is $\epsilon_{u,d,s,g \rightarrow b} = 0.67\%$ for $p_T(j) < 100$ GeV and 2% for $p_T(j) > 250$ GeV. For $100 \text{ GeV} < p_T(j) < 250$ GeV, we linearly interpolate the fake rates given above.

After lepton and jet reconstruction, we demand that the two hard leptons are of the same-sign, a requirement which greatly reduces the SM background, giving a rejection of order 10^{-4} and 10^{-3} for the $t\bar{t}$ and $WWjj$ processes, respectively. After the cuts are imposed, we find a total of 1.0 background event, 0.4 from $t\bar{t}$ and 0.6 from $WWjj$ for 1 fb^{-1} of integrated luminosity.

After b -tagging and restriction to the $\mu^+\mu^+$ mode, 15–30% the signal events survive the analysis cuts depending on the vector mass. Signal and background cross sections are shown in Table 1, before and after cuts, for 6 values of m_V .

Because the decay width of V is narrow,

$$\Gamma(V \rightarrow qq) = \frac{g_{qq}^2 m_V}{24\pi} \left(1 - \frac{4m_q^2}{m_V^2}\right)^{3/2}, \quad (17)$$

one can factor the process $uu \rightarrow t\bar{t}$ into vector production and decay terms,

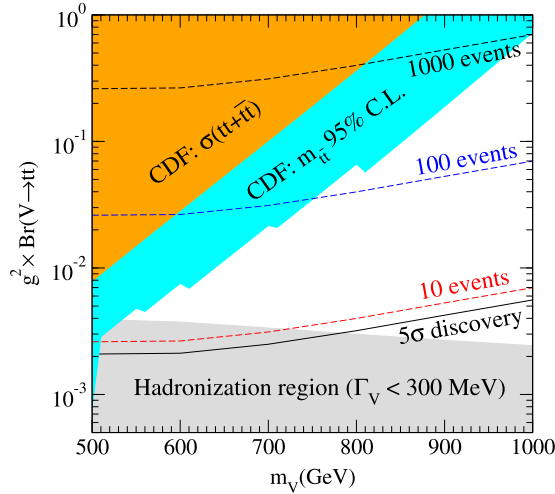


Fig. 2. Event number contours as a function of the vector mass and the parameter $g_{uu}^2 \text{Br}(V \rightarrow tt)$ after all cuts with an integrated luminosity of 1 fb^{-1} . The shaded regions are excluded, as explained in the text.

$$\begin{aligned} \sigma(uu \rightarrow V \rightarrow tt) &= \sigma_0(uu \rightarrow V) \times g_{uu}^2 \text{Br}(tt) \\ &= \sigma_0(uu \rightarrow V \rightarrow tt) \times g_{uu}^2 \frac{\text{Br}(tt)}{\text{Br}_0(tt)}. \end{aligned} \quad (18)$$

The decay branching ratio $\text{Br}(tt) \equiv \text{Br}(V \rightarrow tt)$ is

$$\text{Br}(tt) = \frac{g_{tt}^2 R}{g_{uu}^2 + g_{tt}^2 R}, \quad R = (1 - 4m_t^2/m_V^2)^{3/2}. \quad (19)$$

Subscript “0” denotes the reference value $g_{uu} = g_{tt} = 1$. (Recall, the coupling g_{cc} is assumed to be negligible.) We choose to work with the following two parameters in the rest of this Letter: the vector mass m_V and the product $g_{uu}^2 \text{Br}(V \rightarrow tt)$ via Eq. (18). Based on Poisson statistics, one needs 8 signal events in order to claim a 5σ discovery significance (equivalent to a 99.999943% confidence level) on top of 1 background event. We plot the 5σ discovery line (solid) in the figure. Rates for other values of g_{uu} and g_{tt} can be obtained from Eq. (18).

In Fig. 2, we show the expected numbers of signal events as a function of m_V for a range of values of the coupling $g_{uu}^2 \text{Br}(V \rightarrow tt)$. We obtain the event rate lines by converting the required cross section into $g_{uu}^2 \text{Br}(V \rightarrow tt)$ via Eq. (18). Based on Poisson statistics, one needs 8 signal events in order to claim a 5σ discovery significance (equivalent to a 99.999943% confidence level) on top of 1 background event. We plot the 5σ discovery line (solid) in the figure. Rates for other values of g_{uu} and g_{tt} can be obtained from Eq. (18).

The search for same-sign top quark pair production in the dilepton mode at the Tevatron imposes an upper limit $\sigma(tt + \bar{t}\bar{t}) \leq 0.7 \text{ pb}$ [18–20]. The constraint is plotted in the orange shaded region. The CDF collaboration measured the $t\bar{t}$ invariant mass spectrum in the semi-leptonic decay mode [21]. Since b and \bar{b} jets from $t \rightarrow Wb$ are not distinguished well, tt pairs lead to the same signature as $t\bar{t}$ in the semi-leptonic mode. Hence, the $m_{t\bar{t}}$ spectrum provides an upper limit on $\sigma(tt + \bar{t}\bar{t})$, shown in the cyan shaded region in Fig. 2. The lower gray shaded region is the region in which V would hadronize before decay, washing out the spin correlation effects we utilize to probe the coupling and spin of the sextet state.

4. Top Quark Polarization

We use the observation of a pair of same-sign dileptons as indicative of a same-sign top quark pair and to suppress SM backgrounds efficiently. The two missing neutrinos in the final state complicate event reconstruction. Following Ref. [1], we use the

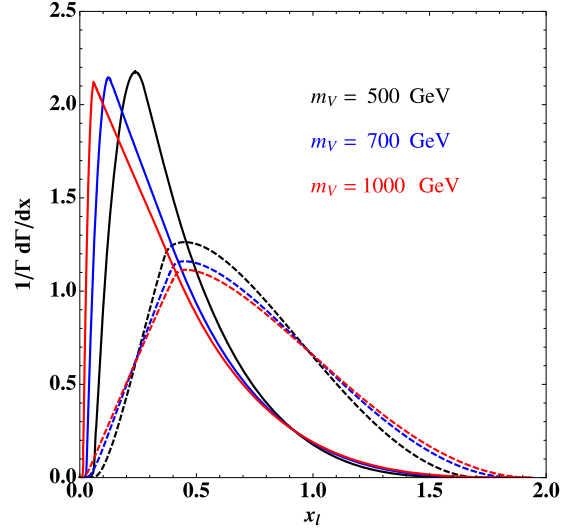


Fig. 3. Normalized distributions of the energy of the charged lepton from top quark decay for $m_V = 500, 700, 1000 \text{ GeV}$. The solid lines correspond to the left-handed top quark decay while the dashed lines to the right-handed top quark decay. The sharp peak in the left-handed top quark decay spectrum moves to lower values as the vector mass increases.

MT2 method [22] to select the correct μ - b combinations and to verify whether the final state is consistent with $t \rightarrow Wb$ parentage. To choose the correct combination, we require the μ - b pairing to be such that M_{T2} is minimized. This choice picks the correct combination with 95% probability. The same method is used successfully in Ref. [23] to determine the top quark mass from a $t\bar{t}$ sample, with both t quarks decaying leptonically. Then we make use of the on-shell conditions of the two W bosons and two top quarks to solve for the neutrino momenta [24,25]. Once the neutrino momenta are known, the kinematics of the entire final state is fixed, and the vector boson mass is computed from the invariant mass of the two reconstructed top quarks.

The next step is to verify that the top quarks exhibit opposite polarization, accomplished here by making use of the difference in the momentum spectra of decay leptons from left-handed and right-handed top quarks [26]. The energy of a charged lepton in a right-handed top quark decay is harder than the one in a left-handed top quark decay. The differential distribution of the charged lepton energy is

$$\frac{d\Gamma}{dx} = \int_{z_{\min}}^{z_{\max}} dz \frac{\partial(x', z')}{\partial(x, z)} \frac{d\Gamma}{dx' dz'}, \quad (20)$$

where $x = 2E_\ell/E_t$ is the energy fraction of the charged lepton, and $z = \cos\theta$ where θ is the helicity angle defined in the Introduction. The variables x' and z' are defined in the top quark rest frame and are linked to x and z in the laboratory frame through the top quark boost:

$$x' = x\gamma^2(1 - z\beta), \quad z' = \frac{z - \beta}{1 - z\beta}, \quad (21)$$

where $\gamma = E_t/m_t$ and $\beta = \sqrt{1 - 1/\gamma^2}$. The lower and upper limits of integration are

$$z_{\min} = \text{Max}\left[\frac{1}{\beta}\left(1 - \frac{1}{\gamma^2 x}\right), -1\right], \quad (22)$$

$$z_{\max} = \text{Min}\left[\frac{1}{\beta}\left(1 - \frac{B}{\gamma^2 x}\right), 1\right]. \quad (23)$$

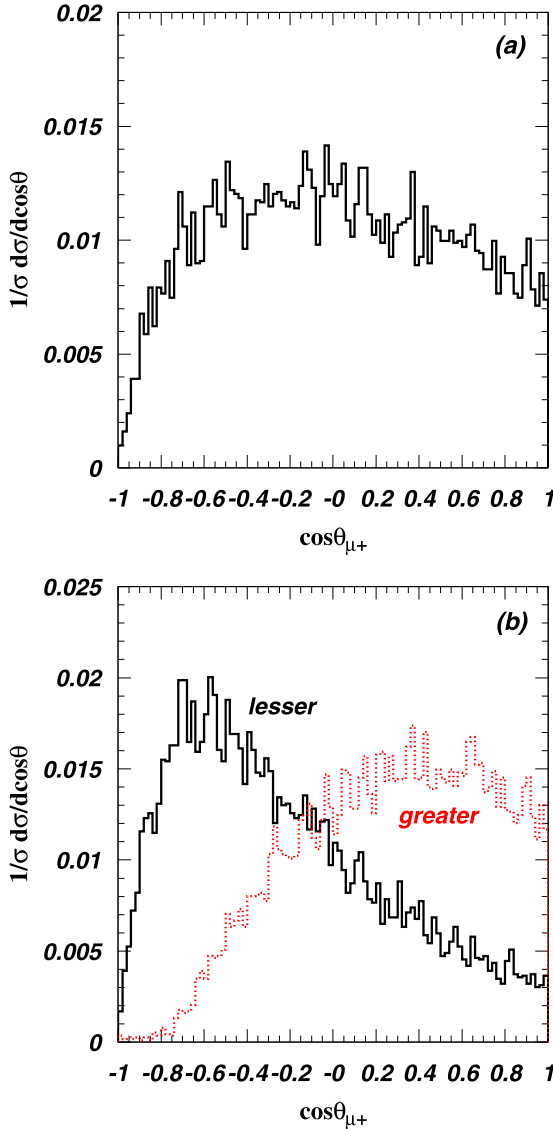


Fig. 4. (a) Distribution in $\cos\theta$ for reconstructed top quarks from $V \rightarrow t_R t_L$ without energy selection on the decay leptons. Both μ^+ leptons exhibit similar distributions. (b) Distribution in $\cos\theta$ for the reconstructed t_{lesser} (black solid) and t_{greater} (dashed (red in the web version)). For illustration we choose $m_V = 600$ GeV.

The differential cross section $d\Gamma/dx'dz'$ in the rest frame of the top quark is [27]

$$\frac{d\Gamma}{dx'dz'} = \frac{\alpha_w^2}{32\pi} \frac{m_t}{AB} x'(1-x') \times \text{ArcTan}\left[\frac{Ax'}{B-x'}\right] \frac{1+\hat{s}_t z'}{2}, \quad (24)$$

where $A = \Gamma_W/m_W$, $B = m_W^2/m_t^2$,

$$\text{ArcTan}(x) = \begin{cases} \arctan(x), & \text{for } x \geq 0, \\ \pi + \arctan(x), & \text{for } x < 0, \end{cases}$$

and \hat{s}_t labels the top quark spin direction. Here, m_W and Γ_W denote the mass and width of the W boson, respectively.

In this work we choose the helicity basis to measure the top quark polarization. In this basis, the top quark spin is chosen to be along (against) the direction of motion of the top quark in

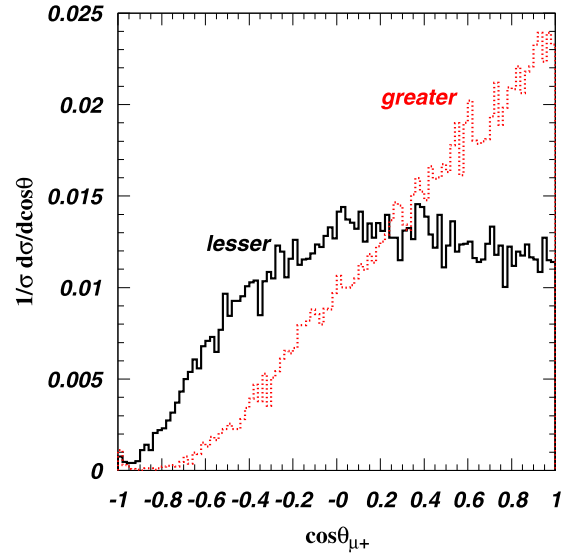


Fig. 5. Distribution of $\cos\theta$ of the reconstructed t_{lesser} and t_{greater} of a singlet scalar decay into $t_R t_R$. For illustration we choose $m_V = 600$ GeV.

the center of mass frame of the system. After a boost from the top quark rest frame to the laboratory frame, we obtain the energy distributions of the charged leptons from left-handed and right-handed top quark decays shown in Fig. 3. The solid curves denote the t_L decay while the dashed curves the t_R decay. As the charged lepton follows the top quark spin, the lepton from t_R decay tends to follow the direction of motion of the top quark, and is more energetic. The lepton from the t_L decay tends to move against the direction of motion of its top quark, and it is therefore less energetic. The difference in the energy spectra becomes more evident with increasing m_V . For example, for a 1000 GeV vector, the charged lepton from t_R decay peaks near $x = 0.5$ while the one from t_L decay peaks below $x = 0.1$. We note that both solid and dashed curves have a kink feature. For the left-handed top quark decay, the kink arises largely from the boost, which generates the lower integration limit z_{\min} . The limit yields a scale of $x \simeq 1 - \beta$ for a heavy vector. On the other hand, the kink in the distribution for right-handed top quark decays comes mainly from the non-continuity of the ArcTan function in the matrix element, which yields a scale of $x \simeq B(1 + \beta)$ after the boost.

In sextet vector boson decay into a $t_L t_R$ pair, the charged leptons exhibit a mixture of the energetic and soft spectra. To utilize this feature, we order the energy of the leptons and define the top quark containing the greater energy lepton as t_{greater} and the other top quark as t_{lesser} . The $\cos\theta$ distributions of the reconstructed t_{lesser} and t_{greater} are displayed in Fig. 4. These results show that one can differentiate the $(1 + \cos\theta)$ (t_R) and $(1 - \cos\theta)$ (t_L) shapes. The reconstruction is not perfect, however, owing to imperfect assignment of the charged lepton. As shown in Fig. 3, charged leptons from t_L decay can be more energetic than those from t_R decay with small probability. With increasing vector mass, the probability of wrong assignment becomes smaller.

As a consistency check on this method for determining polarizations, we apply the same reconstruction to singlet scalar decay into two right-handed top quarks. The reconstructed t_{lesser} and t_{greater} distributions for singlet scalar decay are shown in Fig. 5. Both distributions maintain the expected $(1 + \cos\theta)$ trend, but the shapes are distorted by event reconstruction. Hence, we gain added

confidence that the top quark polarization can be determined and used to discriminate vector bosons from scalar bosons.

5. Summary

We present a study of the search for exotic charge $4/3$ color sextet vector bosons in the production of same-sign top quark pairs at the LHC at 7 TeV. We examine the final states in which both top quarks decay semi-leptonically. We show that vector bosons can be distinguished from scalars. The top quarks from vector decay exhibit opposite polarization, one left-handed and one right-handed. The inclusive distribution in the helicity angle $\cos\theta$ of a charged lepton is flat since it receives contributions from both top quarks. However, we show that an energy selection on the charged leptons can restore the characteristic shapes that distinguish left- and right-handed top quarks. Correspondingly, we show that LHC data should allow one to observe $V \rightarrow t_R t_L$ and distinguish vector from scalar decay.

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